

# UCSF

## UC San Francisco Previously Published Works

### Title

Induction of PNA<sup>d</sup> and N-acetylglucosamine 6-O-sulfotransferases 1 and 2 in mouse collagen-induced arthritis.

### Permalink

<https://escholarship.org/uc/item/7k84z68v>

### Journal

BMC immunology, 7(1)

### ISSN

1471-2172

### Authors

Yang, Jiwei  
Rosen, Steven D  
Bendele, Philip  
et al.

### Publication Date

2006-06-01

### DOI

10.1186/1471-2172-7-12

Peer reviewed

Research article

Open Access

## Induction of PNA<sup>d</sup> and N-acetylglucosamine 6-O-sulfotransferases 1 and 2 in mouse collagen-induced arthritis

Jiwei Yang<sup>1,4</sup>, Steven D Rosen<sup>2</sup>, Philip Bendele<sup>3</sup> and Stefan Hemmerich<sup>\*1,5</sup>

Address: <sup>1</sup>Thios Pharmaceuticals Inc., P.O. Box 20010, Oakland, CA 94620, USA, <sup>2</sup>Department of Anatomy and Program in Immunology, University of California, Box 0452, San Francisco, CA 94143, USA, <sup>3</sup>Bolder BioPATH Inc., University of Colorado, CB 345, Boulder, CO 80309, USA, <sup>4</sup>Current Address: Geron Corporation, 230 Constitution Drive, Menlo Park, CA 94025, USA and <sup>5</sup>Current Address: Y's Therapeutics Inc., 866 Malcolm Rd., Suite no.100, Burlingame, CA 94010, USA

Email: Jiwei Yang - jyang@geron.com; Steven D Rosen - sdr@itsa.ucsf.edu; Philip Bendele - phillip@bolderbiopath.com; Stefan Hemmerich<sup>\*</sup> - s.hemmerich@ysthera.com

<sup>\*</sup> Corresponding author

Published: 13 June 2006

Received: 21 February 2006

BMC Immunology 2006, 7:12 doi:10.1186/1471-2172-7-12

Accepted: 13 June 2006

This article is available from: <http://www.biomedcentral.com/1471-2172/7/12>

© 2006 Yang et al; licensee BioMed Central Ltd.

This is an Open Access article distributed under the terms of the Creative Commons Attribution License (<http://creativecommons.org/licenses/by/2.0>), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

### Abstract

**Background:** Leukocyte recruitment across blood vessels is fundamental to immune surveillance and inflammation. Lymphocyte homing to peripheral lymph nodes is mediated by the adhesion molecule, L-selectin, which binds to sulfated carbohydrate ligands on high endothelial venules (HEV). These glycoprotein ligands are collectively known as peripheral node addressin (PNA<sup>d</sup>), as defined by the function-blocking monoclonal antibody known as MECA-79. The sulfation of these ligands depends on the action of two HEV-expressed N-acetylglucosamine 6-O-sulfotransferases: GlcNAc6ST-2 and to a lesser degree GlcNAc6ST-1. Induction of PNA<sup>d</sup> has also been shown to occur in a number of human inflammatory diseases including rheumatoid arthritis (RA).

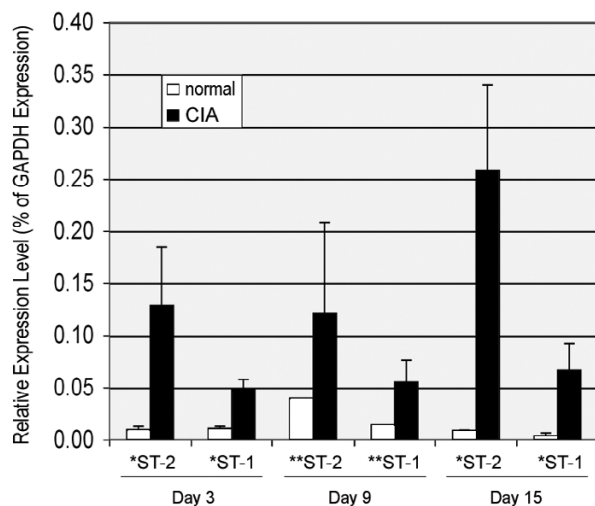
**Results:** In order to identify an animal model suitable for investigating the role of PNA<sup>d</sup> in chronic inflammation, we examined the expression of PNA<sup>d</sup> as well as GlcNAc6ST-1 and -2 in collagen-induced arthritis in mice. Here we show that PNA<sup>d</sup> is expressed in the vasculature of arthritic synovium in mice immunized with collagen but not in the normal synovium of control animals. This de novo expression of PNA<sup>d</sup> correlates strongly with induction of transcripts for both GlcNAc6ST-1 and GlcNAc6ST-2, as well as the expression of GlcNAc6ST-2 protein.

**Conclusion:** Our results demonstrate that PNA<sup>d</sup> and the sulfotransferases GlcNAc6ST-1 and 2 are induced in mouse collagen-induced arthritis and suggest that PNA<sup>d</sup> antagonists or inhibitors of the enzymes may have therapeutic benefit in this widely-used mouse model of RA.

### Background

Chronic inflammatory diseases such as rheumatoid arthritis (RA), asthma, inflammatory bowel disease (IBD), and multiple sclerosis still pose a large unmet medical need despite recent therapeutic advances such as inhaled steroids (asthma) or TNF $\alpha$  antagonists (RA and IBD). Thus, significant subpopulations of patients, in particular

those with severe disease, respond only poorly to these treatments [1,2]. Furthermore, patients treated with TNF $\alpha$  antagonists are at risk for serious infections [3]. Therefore, modulation of leukocyte-endothelial adhesion, an obligatory step in the recruitment of inflammatory cells to lesions, has been widely considered as an alternative and perhaps complementary approach for therapy of chronic



**Figure 1**  
**Expression levels of GlcNAc6ST-1 (ST-1) and GlcNAc6ST-2 (ST-2) in arthritic versus control joints in mouse CIA.** \*  $p < 0.05$ , \*\* only one data point for normal. Error bars represent standard deviations.

inflammation [4,5]. One of the molecules involved in leukocyte trafficking is L-selectin, a member of the selectin family of cell adhesion molecules, which is expressed on leukocytes [6]. During the process of lymphocyte homing to lymph nodes, L-selectin mediates rolling of lymphocytes on high endothelial venules (HEV). This is the first step in a cascade of adhesion and signaling events that culminate in the recruitment of both naïve and central memory lymphocytes into lymph nodes [7]. The major class of ligands recognized by L-selectin consists of a family of sialomucins defined by the adhesion-blocking antibody known as MECA-79. Collectively these ligands are termed peripheral node vascular addressin (PNAd) [8] or sulfoadhesin [9]. One of the shared features of these ligands is 6-O-sulfated N-acetylglucosamine, which is essential for antibody as well as L-selectin binding [10-12]. This modification is found on 6-sulfo sLe<sup>x</sup> which is a minimal recognition determinant for L-selectin [13,14]. The 6-O-sulfation of N-acetylglucosamine of PNAd components occurs in the Golgi compartment and is catalyzed by Golgi-associated N-acetylglucosamine 6-O-sulfotransferases (GlcNAc6STs) [15-17]. Using gene deletion by homologous recombination in mice, we have shown that GlcNAc6ST-2, the high endothelial cell restricted N-acetylglucosamine 6-O-sulfotransferase also known as HEC-GlcNAc6ST, LSST, or GST-3 (gene name *chst4* in mouse) is largely responsible for the GlcNAc-6-sulfation of PNAd and contributes substantially to L-selectin ligand activity and MECA-79 reactivity [18,19]. A related enzyme known as GlcNAc6ST-1 or GST-2 [20] (gene name *chst2*)

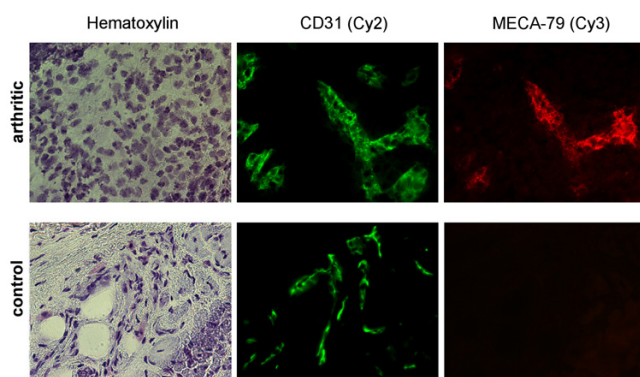
also contributes to sulfoadhesin biosynthesis but to a lesser degree [17,21,22].

While being constitutively expressed in the HEV of lymph nodes and other secondary lymphoid organs, the induction of PNAd has been reported in activated vessels in synovial biopsies from RA patients [23-26], in a model of Lyme disease arthritis in severe combined immunodeficient (SCID) mice infected with *Borrelia burgdorferi* (*B. burgdorferi*) [27], as well as in many other inflammatory lesions [28]. In addition, extralymphoid induction of PNAd in inflammatory lesions was shown to correlate with the de novo expression of GlcNAc6ST-2 in human RA [25] as well as animal models of autoimmunity [16,29]. These findings suggested, that blockade of PNAd, either directly, or indirectly through inhibition of the responsible sulfotransferase(s), might be efficacious for anti-inflammatory therapy [30]. As any drug discovery effort relies on robust and predictive animal models, we have studied the expression of sulfoadhesin and GlcNAc6ST-1 and -2 in murine collagen-induced arthritis (CIA), a widely used animal model which is predictive for therapeutic benefit in human rheumatoid arthritis [31-33]. Our data show that PNAd is expressed in this model in arthritic but not in healthy synovial tissue, and that GlcNAc6ST-1 and 2 are induced in arthritic synovium at the transcript level for both enzymes and at the protein level for at least GlcNAc6ST-2.

## Results

### **GlcNAc6ST-1 and -2 transcript are upregulated in arthritic but not in normal synovium**

In order to investigate the potential relevance of GlcNAc6ST-1 and -2 in the CIA model, we compared the expression of transcripts for these enzymes in arthritic and control synovial tissue by quantitative PCR. We also measured transcripts levels for genes whose expression is known to be upregulated in this model (IL-1 $\beta$  and IL-10) as well as transcript levels for GAPDH, a house keeping gene whose expression does not change in diseased joints [34]. All expression data were normalized to GAPDH levels (% of GAPDH expression). As shown in Fig. 1, GlcNAc6ST-2 transcripts and to a lesser degree GlcNAc6ST-1 transcripts were upregulated in diseased joints compared to control joints at all three time points examined. The mean fold-induction of GlcNAc6ST-2 and GlcNAc6ST-1 in diseased joints as compared to normal joints (all time points pooled) was 11-fold and 6-fold, respectively ( $p < 0.0005$ ). Although levels of GlcNAc6ST-2 transcripts in arthritic joints trended to be higher at day 15 than on day 3 or 9, this difference was not statistically significant. Levels of inflammatory cytokines IL-1 $\beta$  and IL10 were also elevated in diseased as compared to control joints (80-fold and 7-fold, respectively) in agreement with previous reports [35].



**Figure 2**  
**Induction of PNAd in arthritic synovium at day 3.** Sections of knee or ankle joint synovial tissue (obtained at days 3, 9, and 15) and control tissue (from same times and joints) were stained with a CD31 antibody (Cy-2, green), MECA-79 (Cy3, red) and with hematoxylin for bright field visualization. The depicted two-color fluorescence micrographs (400-fold magnification) were taken on sections from day 3 and are representative for the other sections from this time. Sections from days 9 and 15 of the model stained similarly; however, the staining intensity with MECA-79 and the fraction of vessels staining with MECA-79 appeared to be somewhat less than in sections from day 3 (quantitative image and statistical analysis was not performed).

#### **PNAd is induced in arthritic but not in control synovium**

We also probed for presence of PNAd in arthritic and normal synovium by performing immunofluorescence (IF) on cryostat-cut sections of synovial tissue removed from arthritic and control healthy joints (knees and ankles). Five sections were processed from each animal. As shown in Fig. 2, PNAd was strongly induced in a subset of vessels in arthritic synovium. These vessels co-stained with an antibody to CD31, a marker for vascular endothelium [36]. Normal tissue showed CD31<sup>+</sup> vessels, but there was no reactivity of any of the vessels with MECA-79. Frequent PNAd<sup>+</sup> vessels were observed in diseased synovium at all three time points, with staining intensity being slightly higher at day 3 as compared to day 15.

#### **GlcNAc6ST-2 is induced in PNAd<sup>+</sup> vessels in arthritic synovium**

Biosynthesis of the MECA-79 epitope (defining PNAd) in lymph node HEV depends on GlcNAc6ST-2 and to a lesser degree on GlcNAc6ST-1 [18,21,22]. The expression of PNAd in HEV-like vessels within ectopic lymphoid tissue and inflammatory lesions is associated with co-expression of GlcNAc6ST-2 and in at least one site, requires this enzyme [29,37]. Since we had detected PNAd<sup>+</sup> vessels in arthritic synovium (Fig. 2), we probed for GlcNAc6ST-2 protein in these vessels using a peptide-based antibody

[29]. As shown in Fig. 3, GlcNAc6ST-2 was present in a punctuate Golgi-like pattern in PNAd<sup>+</sup> vessels, whereas GlcNAc6ST-2 protein was not detected in synovium from control animals (data not shown).

While in Figure 3 all of the vessels stained by MECA-79 also show at least one instance of punctuate Golgi-staining with the antibody to GlcNAc6ST-2, in other sections we observed a few vessels that exhibited punctuate GlcNAc6ST-2 staining in the absence of MECA-79 reactivity (data not shown). We also noted such a subset of GlcNAc6ST-2 positive but MECA-79 negative vessels in biopsies from human RA patients [25]. As MECA-79 reactivity depends not only on GlcNAc 6-O-sulfation but also on glycosyltransferases, such as the core 1 extension enzyme [38], such structures perhaps reflect a subset of "immature" vessels, which lack additional requirements for recognition by the MECA-79 antibody.

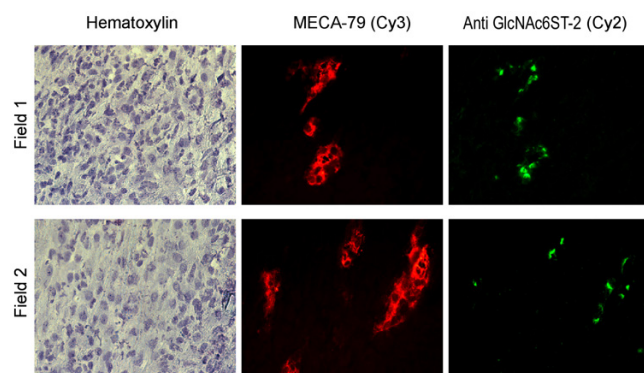
#### **Discussion**

PNAd-expressing vessels, which often feature HEV morphology, have been reported to occur at sites of chronic inflammation (reviewed in references [6] and [28]), where they are believed to facilitate L-selectin-mediated recruitment of naïve and central memory lymphocytes and possibly other leukocytes to the lesions. Significantly, the presence of PNAd has been shown in synovial vessels in human RA [23-26] as well as in a model of Lyme disease arthritis in SCID mice [27]; however, its role in disease processes is unknown. Other than correlative histological evidence, there has been one report implicating L-selectin in the development of arthritis in an animal model [39]. However, a recombinant P-selectin antagonist, which can also bind to L-selectin, was shown to provide protection in the mouse CIA model [40].

Towards the objective of elucidating novel targets for RA therapies, the present study examined the expression of PNAd, and the sulfotransferases, which are involved in its elaboration, in a model of CIA. This model has proven to be predictive for therapeutic benefit in human disease [32].

Using the sulfation-dependent specific antibody MECA-79 in IF, we found PNAd expressed on a large number of synovial vessels in arthritic joints at three evenly spaced time points during the 15 day model but never on synovial vessels from healthy control joints. Furthermore, most of the PNAd<sup>+</sup>-positive vessels demonstrated a punctuate staining pattern for GlcNAc6ST-2 protein, consistent with a Golgi-localization.

In addition, we showed by quantitative PCR that transcripts encoding GlcNAc6ST-2, as well as for the related sulfotransferase GlcNAc6ST-1, were significantly upregu-



**Figure 3**  
**Induction of GlcNAc6ST-2 in PNAd<sup>+</sup> vessels in arthritic synovium at day 3.** Sections of knee or ankle joint synovial tissue (obtained at days 3, 9, and 15 of the model) were stained with MECA-79 (Cy3, red), a GlcNAc6ST-2 antibody (Cy2, green) and with hematoxylin for bright field visualization. The depicted two-color fluorescence micrographs (400-fold magnification) were taken on sections from day 3 after disease onset and are representative for the other sections from this time. Staining patterns observed on sections from day 9 and day 15 were very similar to those from day 3.

lated in rheumatoid synovium as compared to healthy control tissue at all time points examined.

Our data demonstrate for the first time that de novo expression of PNAd together with induction of the endothelial sulfotransferases GlcNAc6ST-1 and -2 are associated with disease in the collagen-induced arthritis model, an established animal model of rheumatoid arthritis widely used in preclinical development of disease-modifying anti-rheumatic drugs (DMARDs). While potential roles of PNAd, as well as GlcNAc6ST-2, in RA have been considered before [25], it remains unclear, whether de novo expression of MECA-79-reactive ligands is causal rather than corollary to the disease process in RA. Significantly, Salmi and colleagues observed MECA-79<sup>+</sup> vessels in human arthritic joints; yet, because of the antibody's inability to significantly inhibit binding of activated mucosal immunoblasts to these vessels, the authors concluded that MECA-79-reactive ligands contributed little to disease-associated leukocyte recruitment [26]. In arthritic joints of SCID mice infected with *B. burgdorferi*, Schaible and coworkers observed the appearance of PNAd only late during infection following early upregulation of other adhesion molecules such as P-selectin, VCAM-1 and ICAM-1 [27]. Therefore these authors hypothesize that migration of leukocytes to inflamed joints in this model depends primarily on P-selectin-mediated rolling with subsequent engagement of  $\alpha 4\beta 1$ /VCAM-1 and LFA-1/ICAM-1. However, we have recently demonstrated the

pathophysiological significance of PNAd<sup>+</sup> vessels in a sheep model of bronchial asthma. Intravenous injection of MECA-79 prior to allergen challenge substantially blocked increases in airway resistance and airway hyperresponsiveness in allergic animals [41]. Use of the MECA-79 antibody in mouse in vivo models would be hampered by the very poor half-life of this rat IgM in the mouse circulation (S. Hemmerich, unpublished observations). Nevertheless, the observed induction of PNAd in the mouse CIA model should motivate alternative approaches to investigate the pathophysiological role of PNAd in RA. Recently, mice have become available which have the GlcNAc6ST-1 gene, the GlcNAc6ST-2 gene, or both inactivated [18,21,22]. The double-null mouse exhibits a complete loss of PNAd from lymph node HEV and a marked but not complete reduction of L-selectin ligand activity. Breeding of this mouse line onto a CIA-susceptible background such as B10RIII or DBA/J [33], should permit investigation of the contribution of PNAd to disease. Alternatively, the availability of an IgG-based antibody with a specificity related to MECA-79 but having improved pharmacokinetics would allow an antibody intervention approach to CIA in the mouse or other species. We and others have recently embarked on discovery of GlcNAc6ST and other sulfotransferase inhibitors by high throughput screening and rational drug design (reviewed in references [30], [42] and [43]). As the CIA model has become the most widely used preclinical animal model for DMARD development [31], positive proof of concept achieved in the target-validation studies discussed above might motivate the development of GlcNAc6ST inhibitors for disease-modifying treatment of RA in humans.

## Conclusion

MECA-79 binding glycoproteins defined as PNAd serve as ligands for L-selectin during the process of lymphocyte homing to lymph nodes. This class of ligands is also critical for inflammatory leukocyte trafficking and the associated disease, as recently demonstrated in a sheep model of asthma. Previous studies in mice have shown the requirement for the sulfotransferases GlcNAc6ST-1 and -2 in generating the MECA-79 epitope and the associated L-selectin ligand activity in HEV and HEV-like vessels. Immunohistochemical analyses have demonstrated ectopic expression of PNAd and GlcNAc6ST-2 in human rheumatoid arthritis. Further investigation into the functional role of PNAd and the requisite sulfotransferases in RA require a suitable animal model. Here we show, that PNAd is expressed de novo in synovial vessels in arthritic joints but not healthy control joints in the CIA model in mice. We further demonstrate that GlcNAc6ST-1 and GlcNAc6ST-2 transcripts are strongly upregulated in diseased tissue in this model and GlcNAc6ST-2 protein is present in a Golgi-associated pattern in the same vessels that show ectopic PNAd expression. Our data suggest the CIA model in mice

for future studies into the functional role of PNAd-mediated leukocyte recruitment in RA and motivate the evaluation of PNAd antagonists or GlcNAc6ST inhibitors for therapeutic benefit in this widely used model of human RA.

## Methods

### Antibodies

The preparation of MECA-79 antibody and the peptide antibody against mouse GlcNAc6ST-2 are described elsewhere [29,41]. Control rat monoclonal IgM JG10.3 was a gift from Dr. Eugene Butcher (Stanford University). Rat anti mouse CD31 IgG2a (MEC13.3) and control rat IgG2a were from BD-Biosciences Pharmingen (San Diego, CA). Control rabbit IgG was from Sigma.

### Arthritis study

#### Animals

18 Male B10RIII mice (Jackson Labs, Bar Harbor, ME), 8  $\pm$  1 weeks on arrival, at least 8 weeks at time of first immunization.

#### Study design and treatment groups

The in vivo study was carried out in its entirety at Bolder BioPATH, Boulder, CO. The study protocol was approved by Bolder BioPATH's Animal Care and Use Committee. Animals (2/group for arthritis, housed 1–2/cage, were acclimated for enough days after arrival to ensure that all mice were at least 8 weeks old. Disease group animals were anesthetized with isoflurane and injected intradermally with 200  $\mu$ g bovine type II collagen (Elastin Products, Owensville, MO) emulsified in 100  $\mu$ l Freund's complete adjuvant (Sigma-Aldrich, St. Louis, MO) with supplemental desiccated *Mycobacterium tuberculosis* H37 Ra (4 mg/ml, Difco Laboratories, Detroit, MI), while normal control group animals were un-manipulated. On days 21–26, onset of arthritis occurred and mice were randomized into groups (Table 1), once swelling was obviously established in at least one paw/joint. Animals were sacrificed and processed for necropsy as specified in Table 1.

#### Necropsy/processing of joints

At necropsy, samples of joint tissue were taken from Groups 1 through 12. Synovium was removed from the outside of the affected joints with periarticular skin (primarily knee and ankle). Synovium from around the patella of affected knees was also taken when possible. Additionally, individual digits showing clinical signs of arthritis were taken whole. All knee and ankle joints that had synovium samples removed were stored in 10% neutral buffered formalin for use in histology. Synovium specimens from Groups 1, 2, 5, 6, 9, and 10, which were chosen for TaqMan Q-PCR expression profiling, were snap frozen and shipped to Thios Pharmaceuticals. Syn-

ovium specimens from Groups 3, 4, 7, 8, 11, and 12 were snap-frozen in a "Gentle Jane" snap freezer (Alphelys, Plaisir, France) and stored at -70°C for Cryostat sectioning (10 slides per animal). Frozen sections were shipped on dry ice to Thios Pharmaceuticals for IF.

### Gene expression profiling by TaqMan real time polymerase chain reaction (Q-PCR)

The Taqman Q-PCR primers and probes (Table 2) for mouse GlcNAc6ST-1 and -2 were designed with Primer-Quest [44] and custom-ordered from Integrated DNA Technologies (Coralville, IA). The PCR efficiency and specificity of the primers was tested at the Genome Analysis Core Facility at the UCSF Comprehensive Cancer Center (San Francisco, CA) prior to use in the experiments.

Prior to processing, synovia from both inflamed and control tissues designated for Q-PCR were brought to -20°C in RNA later-ICE (Ambion, Austin, TX) overnight, and homogenized with TissueMiser (Fisher Scientific, Pittsburgh, PA) in Trizol (Invitrogen, Carlsbad, CA). Total RNA was isolated with Trizol following the manufacturer's instruction. Each cDNA was reverse transcribed from 0.5  $\mu$ g total RNA (random hexamer priming) using the SuperScript III Platinum Two-Step qRT-PCR kit (Invitrogen) according to the manufacturer's instructions. Quantitative RT-PCR (40 cycles, 15 sec at 95°C, 30 sec at 52°C, 30 sec at 72°C, 1 sec at 82°C, read) was performed in triplicate at the Genome Analysis Core Facility at the UCSF Comprehensive Cancer Center using an ABI PRISM 7700 Sequence Detection System (ABI Biosystems, Foster City, CA). All data were normalized to the level of GAPDH transcripts in the same sample. The differences were considered significant when  $p < 0.05$  (Student's T-test).

### Immunofluorescence on synovial tissue sections

Frozen tissue sections received on dry ice from Bolder BioPATH were thawed and brought to room temperature (5 sections per animal). The slides were fixed in ice-cold (0°C) acetone for 5 minutes, and then air-dried at ambient temperature for 30 minutes. Prior to staining, each tissue section was blocked with 5% mouse serum plus 3% bovine serum albumin in phosphate-buffered saline (blocking buffer). All antibodies were diluted in blocking buffer. The working concentration of primary antibodies (MECA-79, anti GlcNAc6ST-2 and anti CD31 and the corresponding isotype-matched control antibodies) was 1  $\mu$ g/ml in all cases. Cy2 or Cy3 labeled secondary antibodies and streptavidin (Jackson ImmunoResearch Laboratories, West Grove, PA) were diluted according to the manufacturer's recommendations. All slides were double-stained either with MECA-79 and CD31 antibodies or MECA-79 and GlcNAc6ST-2 antibodies. PNAd expression was visualized with Cy3-labeled (red) goat anti-ratIgM while CD31 expression was visualized with Cy2-labeled



**Table 1: Disease and control groups in CIA study**

Group	N	Description
1	1	Normal Control for TaqMan Q-PCR(Term and Necropsy Day 3 of Arthritis)
2	2	Disease Control for TaqMan Q-PCR (Term and Necropsy Day 3 of Arthritis)
3	1	Normal Control for IF sections (Term and Necropsy Day 3 of Arthritis)
4	2	Disease Control for IF sections (Term and Necropsy Day 3 of Arthritis)
5	1	Normal Control for TaqMan Q-PCR (Term and Necropsy Day 9 of Arthritis)
6	2	Disease Control for TaqMan Q-PCR (Term and Necropsy Day 9 of Arthritis)
7	1	Normal Control for IF sections (Term and Necropsy Day 9 of Arthritis)
8	2	Disease Control for IF sections (Term and Necropsy Day 9 of Arthritis)
9	1	Normal Control for TaqMan Q-PCR (Term and Necropsy Day 15 of Arthritis)
10	2	Disease Control for TaqMan Q-PCR (Term and Necropsy Day 15 of Arthritis)
11	1	Normal Control for IF sections (Term and Necropsy Day 15 of Arthritis)
12	2	DiseaseControl for IF sections (Term and Necropsy Day 15 of Arthritis)

(green) goat anti-ratIgG. GlcNAc6ST-2 expression was visualized with biotinylated goat anti-rabbit IgG followed by Cy2-labeled streptavidin. Two washings with phosphate buffered saline (PBS) were performed after each antibody incubation. Thereafter, slides were lightly counterstained for 2 seconds with Harris's hematoxylin and mounted with Fluosave (Calbiochem, San Diego, CA). Slides were examined under a Zeiss AxioVert200 microscope and images captured using AxioVision4 software (Carl Zeiss MicroImaging, Inc., Thornwood, NY).

### Abbreviations

*B. burgdorferi*, *Borrelia burgdorferi*; CIA, collagen-induced arthritis; DMARD, disease-modifying anti-rheumatic

drug; GlcNAc6ST, N-acetylglucosamine 6-O-sulfotransferase; HEV, high endothelial venules; IBD, inflammatory bowel disease; IF, immunofluorescence; PNAd, peripheral node vascular addressin; Q-PCR, quantitative polymerase chain reaction; RA, rheumatoid arthritis; SCID mice, severe combined immunodeficient mice.

### Authors' contributions

JY designed and carried out the IF and Q-PCR studies. SDR participated and advised in design and coordination of the study, initiated and supervised the IF with GlcNAc6ST-2 antibodies, and helped in drafting the manuscript. PB had the in vivo portion of the study designed and executed at his institution. SH conceived of and supervised

**Table 2: Primers and probes used for TaqMan Q-PCR**

<b>mouse GlcNAc6ST-1 (GeneBank accession no. <a href="#">NM_018763</a>):</b>	
forward primer	5' CAAGCGGCAGTTGGTGTATGTGTT 3',
reverse primer	5' TTCAGGGCAAAGTCTCCATTTTCG 3',
Taqman probe:	5'ACAGTATGGCCAAGACGCTGCAAACA 3'.
<b>mouse GlcNAc6ST-2 (GeneBank accession no. <a href="#">NM_011998</a>):</b>	
forward primer	5' ATCTTCTGCGTTCCTCTTCTCTGT 3',
reverse primer	5' TTCCTGGCGTTAGTATGGAAGGCA 3',
Taqman probe:	5'TGTGCTAGGGCAGCATTGGAAACGA 3'.
<b>mouse GAPDH (GeneBank accession no. <a href="#">NM_001001303</a>):</b>	
forward primer	5' GAATGGGAAGCTTGTCATCAACGG 3',
reverse primer	5' TAGACTCCACGACATACTCAGCAC 3',
Taqman probe:	5'AAGCCCATCACCATTCTCCAGGAGCGAGA 3'.
<b>mouse IL-1<math>\beta</math> (GeneBank accession no. <a href="#">NM_008361</a>):</b>	
forward primer	5' GTACAAGGAGAACCAAGCAACGAC 3',
reverse primer	5' GTGCCGTCTTTCATTACACAGGAC 3',
Taqman probe:	5'ACCTGTGGCCTTGGGCCTCAAAGGAAAGAA 3'.
<b>mouse IL-10 (GeneBank accession no. <a href="#">NM_010548</a>):</b>	
forward primer	5' ACTGCTATGCTGCCTGCTCTTACT 3',
reverse primer	5' TGGCCTGTAGACACCTTGGTCTT 3',
Taqman probe:	5'AAGCATGGCCCAGAAATCAAGGAGCA 3'.

the study, participated in its design and coordination and drafted the manuscript. All authors read and approved the final manuscript.

## Acknowledgements

This work was supported by National Institutes of Health (NIH) Grants R01-GM57411 and R37-GM23547 (SDR). We thank Annette Bistrup and Stephen Harrison for helpful discussions. We further thank Mark Singer for his advice with GlcNAc6ST-2 antibody IF and Ricarda Finner for critical review of the manuscript.

## References

- Barnes PJ, Woolcock AJ: **Difficult asthma.** *Eur Respir J* 1998, **12(5)**:1209-1218.
- Maini R, St Clair EW, Breedveld F, Furst D, Kalden J, Weisman M, Smolen J, Emery P, Harriman G, Feldmann M, Lipsky P: **Infliximab (chimeric anti-tumour necrosis factor alpha monoclonal antibody) versus placebo in rheumatoid arthritis patients receiving concomitant methotrexate: a randomised phase III trial. ATTRACT Study Group.** *Lancet* 1999, **354(9194)**:1932-1939.
- Giles JT, Bathon JM: **Serious infections associated with anticytokine therapies in the rheumatic diseases.** *J Intensive Care Med* 2004, **19(6)**:320-334.
- Buckley CD, Simmons DL: **Cell adhesion: a new target for therapy.** *Mol Med Today* 1997, **3(10)**:449-456.
- Ward PA, Mulligan MS: **Blocking of adhesion molecules in vivo as anti-inflammatory therapy.** *Ther Immunol* 1994, **1(3)**:165-171.
- Rosen SD: **Ligands for L-selectin: homing, inflammation, and beyond.** *Annu Rev Immunol* 2004, **22**:129-156.
- von Andrian UH, Mempel TR: **Homing and cellular traffic in lymph nodes.** *Nat Rev Immunol* 2003, **3(11)**:867-878.
- Berg EL, Robinson MK, Warnock RA, Butcher EC: **The human peripheral lymph node vascular addressin is a ligand for LECAM-1, the peripheral lymph node homing receptor.** *J Cell Biol* 1991, **114(2)**:343-349.
- Pratt MR, Bertozzi CR: **Syntheses of 6-sulfo sialyl Lewis X glycans corresponding to the L-selectin ligand "sulfoadhesin".** *Org Lett* 2004, **6(14)**:2345-2348.
- Hemmerich S, Bertozzi CR, Leffler H, Rosen SD: **Identification of the sulfated monosaccharides of GlyCAM-1, an endothelial-derived ligand for L-selectin.** *Biochemistry* 1994, **33(16)**:4820-4829.
- Hemmerich S, Butcher EC, Rosen SD: **Sulfation-dependent recognition of high endothelial venules (HEV)-ligands by L-selectin and MECA 79, and adhesion-blocking monoclonal antibody.** *J Exp Med* 1994, **180(6)**:2219-2226.
- Hemmerich S, Rosen SD: **6'-sulfated sialyl Lewis x is a major capping group of GlyCAM-1.** *Biochemistry* 1994, **33(16)**:4830-4835.
- Hemmerich S, Leffler H, Rosen SD: **Structure of the O-glycans in GlyCAM-1, an endothelial-derived ligand for L-selectin.** *J Biol Chem* 1995, **270(20)**:12035-12047.
- Kannagi R: **Regulatory roles of carbohydrate ligands for selectins in the homing of lymphocytes.** *Curr Opin Struct Biol* 2002, **12(5)**:599-608.
- Bistrup A, Bhakta S, Lee JK, Belov YY, Gunn MD, Zuo FR, Huang CC, Kannagi R, Rosen SD, Hemmerich S: **Sulfotransferases of two specificities function in the reconstitution of high endothelial cell ligands for L-selectin.** *J Cell Biol* 1999, **145(4)**:899-910.
- Hiraoka N, Petryniak B, Nakayama J, Tsuboi S, Suzuki M, Yeh JC, Izawa D, Tanaka T, Miyasaka M, Lowe JB, Fukuda M: **A novel, high endothelial venule-specific sulfotransferase expresses 6-sulfo sialyl Lewis(x), an L-selectin ligand displayed by CD34.** *Immunity* 1999, **11(1)**:79-89.
- Kimura N, Mitsuoka C, Kanamori A, Hiraiwa N, Uchimura K, Muramatsu T, Tamatani T, Kansas GS, Kannagi R: **Reconstitution of functional L-selectin ligands on a cultured human endothelial cell line by cotransfection of alpha1-3 fucosyltransferase VII and newly cloned GlcNAc6:6-sulfotransferase cDNA.** *Proc Natl Acad Sci USA* 1999, **96(8)**:4530-4535.
- Hemmerich S, Bistrup A, Singer MS, van Zante A, Lee JK, Tsay D, Peters M, Carminati JL, Brennan TJ, Carver-Moore K, Leviten M, Fuentes ME, Ruddle NH, Rosen SD: **Sulfation of L-selectin ligands by an HEV-restricted sulfotransferase regulates lymphocyte homing to lymph nodes.** *Immunity* 2001, **15(2)**:237-247.
- van Zante A, Gauguier JM, Bistrup A, Tsay D, von Andrian UH, Rosen SD: **Lymphocyte-HEV interactions in lymph nodes of a sulfotransferase-deficient mouse.** *J Exp Med* 2003, **198(9)**:1289-1300.
- Uchimura K, Muramatsu H, Kadomatsu K, Fan QW, Kurosawa N, Mitsuoka C, Kannagi R, Habuchi O, Muramatsu T: **Molecular cloning and characterization of an N-acetylglucosamine-6-O-sulfotransferase.** *J Biol Chem* 1998, **273(35)**:22577-22583.
- Uchimura K, Gauguier JM, Singer MS, Tsay D, Kannagi R, Muramatsu T, von Andrian UH, Rosen SD: **A major class of L-selectin ligands is eliminated in mice deficient in two sulfotransferases expressed in high endothelial venules.** *Nat Immunol* 2005, **6(11)**:1105-1113.
- Kawashima H, Petryniak B, Hiraoka N, Mitoma J, Huckaby V, Nakayama J, Uchimura K, Kadomatsu K, Muramatsu T, Lowe JB, Fukuda M: **N-acetylglucosamine-6-O-sulfotransferases 1 and 2 cooperatively control lymphocyte homing through L-selectin ligand biosynthesis in high endothelial venules.** *Nat Immunol* 2005, **6(11)**:1096-1104.
- Michie SA, Streeter PR, Bolt PA, Butcher EC, Picker LJ: **The human peripheral lymph node vascular addressin. An inducible endothelial antigen involved in lymphocyte homing.** *Am J Pathol* 1993, **143(6)**:1688-1698.
- Middleton J, Americh L, Gayon R, Julien D, Mansat M, Mansat P, Anract P, Cantagrel A, Cattani P, Reimund JM, Aguilar L, Amalric F, Girard JP: **A comparative study of endothelial cell markers expressed in chronically inflamed human tissues: MECA-79, Duffy antigen receptor for chemokines, von Willebrand factor, CD31, CD34, CD105 and CD146.** *J Pathol* 2005, **206(3)**:260-268.
- Pablos JL, Santiago B, Tsay D, Singer MS, Palao G, Galindo M, Rosen SD: **A HEV-restricted sulfotransferase is expressed in rheumatoid arthritis synovium and is induced by lymphotoxin-alpha/beta and TNF-alpha in cultured endothelial cells.** *BMC Immunol* 2005, **6(1)**:6.
- Salmi M, Rajala P, Jalkanen S: **Homing of mucosal leukocytes to joints. Distinct endothelial ligands in synovium mediate leukocyte-subtype specific adhesion.** *J Clin Invest* 1997, **99(9)**:2165-2172.
- Schaible UE, Vestweber D, Butcher EG, Stehle T, Simon MM: **Expression of endothelial cell adhesion molecules in joints and heart during Borrelia burgdorferi infection of mice.** *Cell Adhes Commun* 1994, **2(6)**:465-479.
- Rosen SD: **Endothelial ligands for L-selectin: from lymphocyte recirculation to allograft rejection.** *Am J Pathol* 1999, **155(4)**:1013-1020.
- Bistrup A, Tsay D, Shenoy P, Singer MS, Bangia N, Luther SA, Cyster JG, Ruddle NH, Rosen SD: **Detection of a sulfotransferase (HEC-GlcNAc6ST) in high endothelial venules of lymph nodes and in high endothelial venule-like vessels within ectopic lymphoid aggregates: relationship to the MECA-79 epitope.** *Am J Pathol* 2004, **164(5)**:1635-1644.
- Hemmerich S: **Carbohydrate sulfotransferases: novel therapeutic targets for inflammation, viral infection and cancer.** *Drug Discov Today* 2001, **6(1)**:27-35.
- Brand DD, Kang AH, Rosloniec EF: **Immunopathogenesis of collagen arthritis.** *Springer Semin Immunopathol* 2003, **25(1)**:3-18.
- Moore AR: **Collagen-induced arthritis.** *Methods Mol Biol* 2003, **225**:175-179.
- Myers LK, Rosloniec EF, Cremer MA, Kang AH: **Collagen-induced arthritis, an animal model of autoimmunity.** *Life Sci* 1997, **61(19)**:1861-1878.
- Plater-Zyberk C, Buckton J, Thompson S, Spaul J, Zanders E, Papworth J, Life PF: **Amelioration of arthritis in two murine models using antibodies to oncostatin M.** *Arthritis Rheum* 2001, **44(11)**:2697-2702.
- Stasiuk LM, Abelsira-Amar O, Fournier C: **Collagen-induced arthritis in DBA/1 mice: cytokine gene activation following immunization with type II collagen.** *Cell Immunol* 1996, **173(2)**:269-275.
- DeLisser HM, Newman PJ, Albelda SM: **Molecular and functional aspects of PECAM-1/CD31.** *Immunol Today* 1994, **15(10)**:490-495.



37. Drayton DL, Ying X, Lee J, Lesslauer W, Ruddle NH: **Ectopic LT alpha beta directs lymphoid organ neogenesis with concomitant expression of peripheral node addressin and a HEV-restricted sulfotransferase.** *J Exp Med* 2003, **197(9)**:1153-1163.
38. Yeh JC, Hiraoka N, Petryniak B, Nakayama J, Elies LG, Rabuka D, Hindsgaul O, Marth JD, Lowe JB, Fukuda M: **Novel sulfated lymphocyte homing receptors and their control by a Core1 extension beta 1,3-N-acetylglucosaminyltransferase.** *Cell* 2001, **105(7)**:957-969.
39. Szanto S, Gal I, Gonda A, Glant TT, Mikecz K: **Expression of L-selectin, but not CD44, is required for early neutrophil extravasation in antigen-induced arthritis.** *J Immunol* 2004, **172(11)**:6723-6734.
40. Sumariwalla PF, Malfait AM, Feldmann M: **P-selectin glycoprotein ligand I therapy ameliorates established collagen-induced arthritis in DBA/1 mice partly through the suppression of tumour necrosis factor.** *Clin Exp Immunol* 2004, **136(1)**:67-75.
41. Rosen SD, Tsay D, Singer MS, Hemmerich S, Abraham WM: **Therapeutic targeting of endothelial ligands for L-selectin (PNAd) in a sheep model of asthma.** *Am J Pathol* 2005, **166(3)**:935-944.
42. Hemmerich S, Verdugo D, Rath VL: **Strategies for drug discovery by targeting sulfation pathways.** *Drug Discov Today* 2004, **9(22)**:967-975.
43. Rath VL, Verdugo D, Hemmerich S: **Sulfotransferase structural biology and inhibitor discovery.** *Drug Discov Today* 2004, **9(23)**:1003-1011.
44. Primerquest: **Primerquest.** *PrimerQuest* (<http://scitoolsidtdnacom/Primerquest/>) 2006.

Publish with **BioMed Central** and every scientist can read your work free of charge

"BioMed Central will be the most significant development for disseminating the results of biomedical research in our lifetime."

Sir Paul Nurse, Cancer Research UK

Your research papers will be:

- available free of charge to the entire biomedical community
- peer reviewed and published immediately upon acceptance
- cited in PubMed and archived on PubMed Central
- yours — you keep the copyright

Submit your manuscript here:  
[http://www.biomedcentral.com/info/publishing\\_adv.asp](http://www.biomedcentral.com/info/publishing_adv.asp)

